Advances in Water Resources 115 (2018) 301–314

Contents lists available at ScienceDirect

Advances in Water Resources

journal homepage: www.elsevier.com/locate/advwatres

Fostering cooperation in power asymmetrical water systems by the use of direct release rules and index-based insurance schemes

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ARTICLE INFO

Keywords:
Water management
Hydroeconomics
Index-based insurance
Cooperation
Power asymmetry

ABSTRACT

In river basin systems, power asymmetry is often responsible of inefficient and unbalanced water allocations. Climate change and anthropogenic pressure will possibly exacerbate such disparities as the dominant party controls an increasingly limited shared resource. In this context, the deployment of cooperation mechanisms giving greater consideration to a balanced distribution of the benefits, while improving system-wide efficiency, may be desirable. This often implies the intervention of a third party (e.g., the river basin water authority) imposing normative constraints (e.g., a minimum release) on the party in the dominant position. However, this imposition will be more acceptable to the dominant party if coupled with some form of compensation. For a public agency, compensation may be burdensome, especially when the allowance is triggered by natural events whose timing and magnitude are highly uncertain. In this context, index-based insurance contracts may represent a viable alternative and reduce the cost of achieving socially desirable outcomes. In this paper, we develop a hybrid cooperation mechanism composed of i) a direct normative constraint imposed by a regulator, and ii) an indirect financial tool, an index-based insurance contract, to be used as a compensation measure. The approach is developed for the Lake Como multi-purpose water system, Italy: a complex Alpine river basin, supporting several hydropower reservoirs and finally flowing into a regulated lake which supplies water to several downstream uses, mostly irrigated agriculture. The system is characterized by a manifest geographic power asymmetry: the upstream hydropower companies are free to release their stored water in time irrespective of the timing of the downstream demands. This situation can lead to financial losses by the downstream users and undesirable social outcomes. Results suggest that financial instruments may offer a reliable and relatively inexpensive alternative to other forms of compensation, and thereby favor more balanced management of multi-purpose water systems characterized by power asymmetry. This finding is especially relevant in times when granting of licenses to use/withdrawal water are often being reviewed with attention to environmental protection and equity issues.

1. Introduction

In many river basins, different stakeholders depending on the same resource do not share equal power position: when the resource is scarce or its use is competitive among multiple agents, power distribution becomes pivotal in shaping water sharing policies (Espey and Towfique, 2004; Song and Whittington, 2004; Zawahri and Gerlak, 2009; Zawahri and Mitchell, 2011). Power asymmetry has been extensively studied in the water resources literature, especially for international transboundary contexts (Daoudy, 2009; Dinar et al., 2007; Dinar, 2009; Zeitoun et al., 2011). A commonly accepted definition of power is still debated (Evans and Newnham, 1998), yet generally it is viewed as encompassing different dimensions: hard or "structural" power such as geographical location is distinguished from political, soft power (Nye, 2008) and "sticky" economic power (Mead, 2004). Nonetheless, in both national and international cases, geographic position and flow control, together with vested water rights, are intrinsically present and always play a role in upstream/downstream water disputes (Kehl, 2015; Mandel, 1992). For this reason, particularly when water scarcity is exacerbated by climatic extremes or varying socio-economic conditions (e.g., drought and/or increased water demands), power asymmetry can be responsible for socially inequitable and inefficient water allocations (Zeitoun et al., 2011). In these cases, a third party, in the form of a regulatory actor (e.g., the river basin water authority) may decide to

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http://dx.doi.org/10.1016/j.advwatres.2017.09.021
Received 25 May 2017; Received in revised form 24 August 2017; Accepted 24 September 2017
Available online 27 September 2017
0309-1708/ © 2017 Published by Elsevier Ltd.

intervene by restricting or controlling the behaviors of water users (Browder, 2000; Dinar and Alemu, 2000; Dinar, 2000; Elhance, 2000). However, adopting direct regulation to enforce power balance and water redistribution may be highly controversial or infeasible, due to resulting unilateral losses and vested water rights. Typically, the imposed new regulatory regime favors one agent at the expense of another, therefore, to improve its acceptability, some form of compensation is helpful (Dinar, 2006). As far as different water uses are concerned, the benefits generated by the constraint for one agent and the global system is often non-transferable to the agent negatively affected by the constraint (Madani et al., 2014). Therefore, improving system equality usually comes at a price for the public authority, often in the form of direct monetary indemnity (Arjoon et al., 2016; Mitchell and Keilbach, 2001). This form of compensation can be burdensome, especially when the allowance is triggered by natural events whose timing and magnitude are unknown in advance. In this context, index-based insurance contracts may represent a viable option and offer a less expensive tool for achieving the desired, presumably more balanced, outcome. Index-based, or parametric, insurance is a particular type of financial instrument in which the payout is not conditioned on actual losses but rather triggered by the value of an independent and transparent index (Goodwin, 2001). The use of an index insurance contract, in place of a traditional indemnity-based contract, reduces the risk of adverse selection i.e., asymmetric information between buyer and seller that leads to a contract more biased toward one sector, given the buyer has no control on the index (Hazell and Skees, 2006). It also eliminates the need of skilled experts to assess the insured's actual losses and the information required to be set is limited (Barnett and Mahul, 2007). On the other hand, index-based insurance requires a high level of correlation between the index and actual losses as any significant deviation will lead to uncovered damages or unnecessary payouts, a situation described as demonstrating high "basis risk" (Woodard and Garcia, 2008).

Recent years have witnessed an increased interest in index-based contracts as mechanisms for sharing risks due to weather phenomena (i.e., weather derivatives) (Alderman and Haque, 2007; Barnett et al., 2008; Brockett et al., 2005; Carter et al., 2014; Manfredo and Richards, 2009; Turvey, 2001). Applications are numerous and diverse, ranging from hedging solutions for the demand fluctuations in electricity (Martin et al., 2001) to supporting agriculture in developing countries (Bryla-Tressler et al., 2011; Hess et al., 2002; Rao, 2010). As far as water management is concerned, index-based insurance has been proposed as a tool to reduce water-related fluctuations of revenues and costs for water utilities, as well as hydropower companies (Foster et al., 2015; Zeff et al., 2014), and to increase available funds for purchasing water from spot markets and option contracts (Brown and Carriquiry, 2007; Leiva and Skees, 2008) or to support groundwater pumping costs (Kemeze et al., 2016). State-of-the-art examples of the adoption of financial tools as a compensation measure for water restrictions at the river-basin level are relatively recent and mostly directed towards environmental issues. In Kern and Characklis (2017) index-based insurance contracts are used to compensate hydropower companies for ramp-rate limitations aimed at obtaining more stable, environmentally friendly water releases downstream. A traditional drought insurance scheme is applied in Pérez Blanco and Gómez Gómez (2013) to prevent farmers from illegal groundwater abstractions in dry years.

In this paper, we design a hybrid cooperation mechanism (HCM) for competing stakeholders in a river basin affected by geographic power asymmetry, i.e., with upstream riparians taking advantage of their position by acting unilaterally at the expense of downstream users. The HCM combines two different measures i) a direct, normative constraint imposed by a regulator on the upstream riparians and ii) an indirect compensatory financial tool. The HCM's ability to redistribute water rights and induce cooperation in upstream and downstream management, as well as its feasibility and acceptability, are evaluated and compared to a scenario with no insurance.

The methodology is developed for the Lake Como system in Italy. Lake Como is a complex Alpine river basin, whose topology can be divided into three parts: a large upstream watershed, where numerous hydropower plants exploit the varied terrain for electricity production; a deep glacial regulated lake in the middle; and several water users, mostly farmers, downstream. The lake is regulated with the primary purpose of allocating water to the downstream irrigation districts while guaranteeing flood protection to the city of Como. The system is affected by a manifest geographic power asymmetry, given the upstream hydropower companies are granted licenses to freely release their stored water in time irrespective of the timing of downstream users' demands. This conflicting situation is exacerbated during summer droughts, when farmers may bear consistent financial losses while upstream hydropower reservoirs are still retaining their storage for winter electricity demands. In 2003 and 2005, extremely dry circumstances led the Regional Water Authority to impose forced releases on several upstream hydropower companies to relieve farmers' water deficit. The emergency measure brought little benefit to the crops, but resulted in significant economic losses for the hydropower companies. As a consequence, they started a lawsuit that was later settled with the Regional Authority having to pay hydropower producers compensation, given the release order was not compliant with the companies abstraction licenses (Anghileri et al., 2012).

In this context, we design a HCM combining i) a dynamic minimum release constraint and ii) an index-based insurance scheme. The former, is imposed by the third party (i.e., the Regional Water Authority) on the upstream hydropower companies, in order to provide basic water deficit relief to the downstream farmers in dry circumstances, when the geographic power asymmetry tends to generate unbalanced situations. We explored different release constraints of varying severity, corresponding to different trade-off solutions of a multi-objective management problem differently balancing both upstream and downstream benefits. Concurrently, the insurance scheme is designed to offset the upstream party loss by providing the hydropower companies with a tool for managing supply risk, i.e., the financial risk associated with supply availability fluctuations, which in this case are linked to hydrology (water availability). The HCM is finally evaluated in all its parts and compared to a direct form of compensation.

The paper is organized as follows: Section 2 describes the approach adopted to design the normative constraint and the index-based financial contracts as parts of the Hybrid Cooperation Mechanism. Section 3, introduces the application context as well as the model used to simulate and evaluate the HCM performance. Afterwards, the numerical results are presented in Section 4 where the index-based contracts are also compared to other forms of compensation. Final conclusions are drawn in Section 5.

2. Materials and methods

We designed and evaluated a hybrid cooperation mechanism following the methodology reported in Fig. 1, where, for the sake of clarity, we assume competing agents who independently manage water storage on the same river under geographic power asymmetry conditions (see the inner panel). The upstream users operate their reservoirs as profit maximizers (i.e., income from hydropower). The downstream agent is also acting individually to attempt maximizing the benefit of water supply, but conditionally based on the upstream users decisions. A similar scheme is common to several water basins where a consumptive water use downstream is conditioned by the upstream individualistic release policies.

A conceptual model of the water system, able to describe both the hydrological and the economic component (see Section 3.2), is employed under two different cooperation settings: fully cooperative (FC) and uncooperative (UC). Fully cooperative is intended as the situation in which the agents adopt the maximum level of cooperation as defined by Watkins (2006) i.e., they take joint actions to pursue global

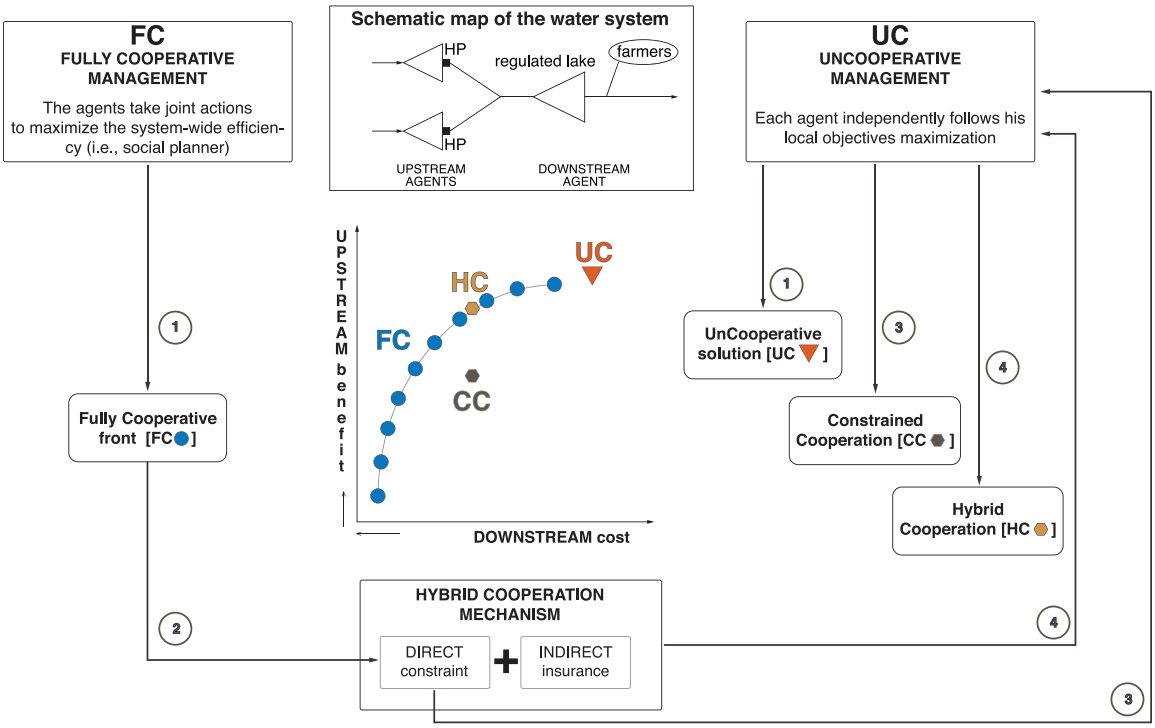

Fig. 1. Procedure flow chart. 1) The system operation design is performed under two opposite configurations: Fully Cooperative (FC) and UnCooperative UC, producing the FC_i set and the uncooperative UC solution respectively. 2) the FC solutions' releases are analyzed to extract a direct constraint on the upstream release; the UC policy is simulated under the direct constraint to produce the corresponding CC_i solution. 3) A financial hedging contract is designed to act as a compensation measure for the upstream constraint-induced losses; the coupled simulation of the constraint and the insurance (i.e., the hybrid cooperation mechanism) produces the improved solution *HC*.

efficiency. This is equivalent to assuming the existence of a social planner who optimizes all the agents' objectives at the same time, i.e. pursue system-wide efficiency by solving a multi-objective problem. At the other end of the spectrum, the uncooperative scenario represents a situation in which each agent independently optimizes its own utility without interacting, yet still possibly affecting, the others. Specifically, the downstream agents maximize their benefits by using inflows whose timing and magnitude are determined by the upstream agents' self-interested release decisions.

Typically, if the water system is affected by power asymmetry and the agents have conflicting interests, the UC management scenario will determine a solution whose performance is strongly biased towards the most powerful agent (Zeitoun and Warner, 2006). On the other hand, a FC management scenario will produce a set of Pareto efficient, yet ideal, solutions FC_i, whose performance vary depending on the adopted trade-off among the conflicting agents' interests (Giuliani et al., 2015). In this respect, the UC solution represents one of the extremes of the FC Pareto front and, as such, is a Pareto system-wide efficient solution. Yet, Pareto efficiency does not imply equity as distributive justice, corresponding to a more balanced and politically acceptable solution distributing the costs of droughts among all the stakeholders.

The design of a hybrid cooperation mechanism (HCM) has the role of finding a politically acceptable compromise alternative between an unbalanced UC solution and an unrealistically acceptable FC one. The first component of the mechanism is a direct normative constraint on the upstream agents' releases (arrow 2 in Fig. 1) to shift the UC trade-off towards the disadvantaged downstream agent. Imposing such a normative constraint in the UC scenario serves to counteract the UC power asymmetry and produces a new constrained cooperative solution (CC_i and arrow 3 in Fig. 1).

The potential revenue loss, which is induced by the normative release restrictions on the upstream agents' decisions, is then addressed by the second component of the HCM (arrow 4 in Fig. 1) in the form of a financial hedging contract (e.g., an index-based insurance). The new compromise solution *HC* is expected to reduce power asymmetry by constraining the upstream agents' decisions to favor the downstream performance, while being accepted by the upstream agents thanks to the compensation provided by the insurance payouts.

In the next paragraphs, the two components of a hybrid cooperation mechanism design are described in detail, while the water system model and the optimization approach are presented in Section 3.

2.1. Fully cooperative and uncooperative solutions

Given the presence of multiple agents, a multi-objective optimization algorithm is adopted in order to identify the optimal operating policies under different cooperative scenarios (arrow 1 in Fig. 1). Each cooperative scenario corresponds to an alternative solution (FC_i) to the multi-objective FC problem and represents a different trade-off between the agents. A large and complex river basin is likely to be managed by many agents independently, each one optimizing their local objectives (Madani, 2010; Tilmant and Kinzelbach, 2012). For this reason, the current baseline is assumed to be the uncooperative alternative (*UC*), i.e., the optimal strategy emerging from the UC management scenario. This UC solution is then benchmarked against the set of Pareto efficient FC alternatives.

Depending on the management context (UC or FC), a different problem, or a combination of problems, is solved to design the optimal operation for the upstream and downstream users. In general, the optimization problem consists in finding the best operating policy π^* such that

$$\pi^* = \arg\min_{\pi} \mathbf{J} \tag{1}$$

where the policy π is defined as a closed loop control policy (Castelletti et al., 2008) that determines the release decision $u_t = \pi(d_t, \mathbf{x}_t)$ at each time step t as dependent on the day of the year d_t which informs on the natural and the anthropic time, and the current state $\mathbf{x}_t$ of the modeled system (e.g., the lake/reservoir level). The

release decision u_t may differ from the actual release r_{t+1} in specific situations, where normative and physical constraints may restrict the ability of the dam operator to subjectively regulate the system. The objectives vector **J** to be minimized is defined for each problem based on the management configuration. In fact, while in an UC configuration each agent minimizes his individual management goals, in a FC scenario a system-wide multi-objective perspective is adopted.

2.2. The direct component: dynamic minimum release constraint

We adopt the approach proposed by Anghileri et al. (2012) to design a dynamic release constraint aimed at establishing a mutual influence among upstream and downstream users in place of the current one-sided dependence. The constraint imposes a forced minimum volume release to the upstream agents that is triggered and adjusted by downstream water availability (e.g., the storage in the downstream reservoir). The core of the constraint design is the analysis of the upstream/downstream relationship that is observed in a FC management context: unlike the UC policy, where the upstream release decisions are indifferent to the downstream condition, and can, therefore, assume whichever possible value, a fully cooperative solution will only display a set of upstream decisions that are compatible with the given downstream target.

Presumably, in a FC_i solution corresponding to a trade-off favoring the downstream performance, when there is limited water available to meet downstream needs, the upstream agents never release less than a given volume. The constraint is designed in order to mimic this relationship in an UC context. The dynamic minimum release rule is extracted from the analysis of the trajectories of the upstream releases and the corresponding downstream storage in a FC_i solution. The minimum upstream release observed in association to each value of the downstream storage is set as the minimum release constraint to be imposed in the UC scenario. A different rule can be extracted from each FC_i alternative to mimic different preference levels toward achieving the downstream goal.

2.3. The indirect component: index-based insurance contract

In cooperative game theory (Parrachino, 2006) among the conditions for a new allocation scheme to be practicable is that the benefits of cooperation to any stakeholder are at least equal to what that stakeholder would obtain by acting independently (i.e., individual rationality). In this case, we want to design a mechanism able to incentivize a shift from the current unbalanced equilibrium outcome to a more politically acceptable alternative. This shift, enforced by the first component of the HCM, is made acceptable through an index-based insurance contract. The financial solution is offered to the upstream agents for covering the losses generated by the dynamic minimum release constraint.

In recent years, increasing interest has been devoted to the use of index-based derivatives as tools for managing risks related to climate and weather phenomena (Brockett et al., 2005; Manfredo and Richards, 2009). Index-based insurance is an alternative form of insurance, in which the payout is triggered and based on the values measured from an index (usually a weather or hydrologic variable) as opposed to the assessed damage of each insurance buyer. When the index is suitably selected, it acts as a proxy for the losses, offering some advantages over more traditional forms of insurance. By eliminating the need of skilled experts required to assess the insured's actual losses, index-based derivatives are able to cut transaction costs, a feature that made them suitable for the adoption in many international cooperation projects in the developing world (Barnett and Mahul, 2007). Moreover, since the payout is triggered by an independent weather parameter, which cannot be influenced or manipulated by the buyer, the use of an index insurance contract reduces the risk of adverse selection and moral hazard (Skees, 2011). However, being a relatively new concept in water related sectors, the adoption of index-based contracts requires education among the stakeholders, in order to help them understanding the advantages and shortcomings of such financial products (Smith and Watts, 2009). Prerequisites for a viable index-based insurance scheme are data availability and reliability, and a good correlation between the payout and the actual loss, i.e., to avoid what is referred to as basis risk (Skees, 2011).

The practical steps to be followed in designing an index-based insurance contract are briefly described in the next paragraphs.

a. Setting the index

The most important and critical part of setting an insurance contract is the selection of an appropriate underlying index. The index must be a measurable and transparent metric that correlates well with the financial loss that the insurance is covering. When the index fails to describe losses, the resulting basis risk is borne by either the buyer (the index underestimates damage) or the seller (the index overestimates damage). The index must also be free of concerns over manipulation to prevent moral hazard and insurance fraud (Miranda and Vedenov, 2001). While any good index-based contract should aim at a low basis risk, in some cases a trade-off between the complexity of an index and its basis risk is observed. In the literature, the index is identified according to the nature of the covered financial loss: the inflow (Foster, 2013; Foster et al., 2015; Zeff et al., 2014) or a combination of the inflow and other external electricity peak price drivers (e.g., natural gas prices, being the least expensive peaking source after hydropower, are one of these drivers (Kern et al., 2015)) are usually good at describing hydropower production losses; rainfall (Giné et al., 2008), temperature, humidity (Hellmuth et al., 2009), and remote sensed vegetation indices (Patankar, 2011) typically correlate well with crop losses; wind speed and tremor level are suitable in case of hurricane and earthquake losses (Bichara, 2007); river levels are often used to describe flood related damage (Hellmuth et al., 2009).

b. Defining the payout function

The payout function defines the conditions under which a contract buyer receives a payout, as well as the magnitude of the payout. According to the level of coverage desired by the insured party, an index threshold, or strike, is set. A payout is triggered each time the measured index crosses the strike and the magnitude of the payout is defined through a function. Based on the type of payout function, different contract categories are defined. In our application, we designed insurance contracts. In this case, the payout is based on the difference between the strike S and the measured index i: the farther the index value falls below the strike, the higher the payout:

$$p = \begin{cases} A \cdot [max(S - i, 0)] & \text{if } i < S \\ 0 & \text{otherwise} \end{cases} \quad (2)$$

where p is the payout and A is the slope of the linear portion of the payout function.

The strike and the slope can be determined in a variety of ways: the former can be set as a random threshold or as a percentile of the index; the latter should be an economic variable related to the index.

c. Pricing the contract

A third party (e.g., insurance company) would set the contact price or premium (P) by estimating the expected payout $E[p]$ from the payout distribution plus the loading (L), an additional amount reflective of concerns over the uncertain timing and magnitude of payouts (i.e., the risk aversion of the insurer) and to account for both administrative costs and the opportunity costs of maintaining the reserves necessary to make payouts (Smith and Watts, 2009).

$$P = E[p] + L \quad (3)$$

One method for computing the price of a contract in weather derivatives is the Wang transform (Wang, 2002). This approach converts the payout distribution to "risk neutral" using a distortion equation which more heavily weights the high end of the original payout pdf ($F(p)$) (Wang, 2000). The risk adjusted payout function $F^*(p)$ is determined as:

$$F^*(p) = \phi(\phi^{-1}(F(p)) + \lambda) \quad (4)$$

where ϕ is the standard cumulative distribution and λ is the Sharpe ratio or the market price of risk (Wang, 2002). Large payouts that occur with low probability have larger capital and liquidity requirements, and maintaining these reserves represents an opportunity cost for the insurer. Weighting these tail events more heavily increases the expected costs of the insurer to a value that accounts for both payouts to the policyholder and the contract loading. The adjusted premium $P(p)$ is defined as:

$$P(p) = \sum p \cdot F^*(p) \quad (5)$$

As a consequence, as the variance of a payout distribution grows, the difference between the premium and the expected value of payouts (i.e., the loading) increases.

d. Timing

The contract timing is characterized by three stages: (1) the contract terms are established and the premium paid at the execution date, (2) the contract index starts to be measured on the effective date and (3) finishes on the maturity date, when the payout is computed as specified by the index value on maturity date and the payout structure. The time distance between the execution and the effective dates must guarantee that no prediction on the index is available to any party in the contract (Foster et al., 2015).

3. Case study

3.1. System description

Lake Como (Fig. 2) is the third largest lake in Italy with a total volume of 234 $\times 10^8$ m^3, of which 2.54 $\times 10^8$ m^3 are regulated through a dam on the outflowing Adda river. The river serves a dense network of downstream irrigation canals, which convey water to four agricultural districts with a total surface of 1400 km^2, mostly growing maize. The same releases are also sufficient to feed eight run-of-river hydroelectric power plants. The lake releases are managed from 1946 by the Adda Consortium with the twofold purpose of water allocation to the downstream users and flood protection along the lake's shoreline, particularly in Como city (Galelli and Soncini-Sessa, 2010).

The lake is fed by a 4552 km^2 Alpine watershed characterized by a highly varied terrain elevation, which provides a significant hydropower potential exploited through 26 small to medium artificial reservoirs operated by different power companies. With a total storage of 5.45 $\times 10^8$ m^3, more than twice the active capacity of the lake, the alpine reservoirs have a significant influence on the downstream streamflow and therefore on the lake water availability in time. Specifically, the lake inflow regime is affected by the upstream reservoirs whose releases are moving water volumes through seasons.

The natural hydro-meteorological regime is characterized by a double peak pattern: one more pronounced peak corresponding to the snow-melt season, in late spring, and another, more variable, produced by autumn rains. For both the lake and the hydropower reservoirs, the snow-melt represents the main contribution to the creation of seasonal storage. However, the result of the combined upstream reservoirs' release policies is often conflicting with the lake water allocation goals: in summer, when agricultural irrigation demand is at its maximum, the upstream reservoirs, filled with the contribution from the snow-melt,

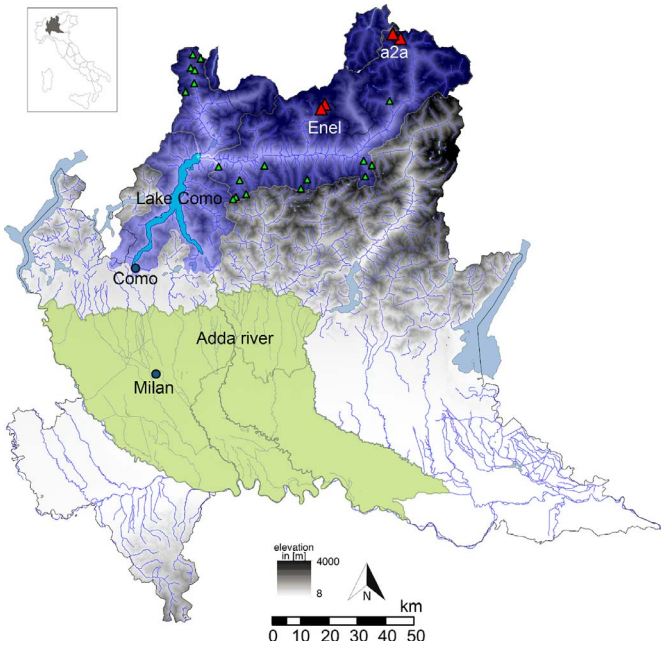

Fig. 2. Map of the study area: Lake Como, the watershed area (violet), and downstream agricultural districts (green). The triangles denote hydropower reservoirs (the red ones are the four reservoirs considered in this study and managed by a2a and Enel). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

limit their releases to profit by higher electricity prices in winter. This conflict has been exacerbated by the advent of renewables and particularly after 2009, when the Italian government largely subsidized solar power production (GSE, 2011). As a result, hydropower production was extensively allocated to fill the sharpened electricity price peaks in winter, further reducing summer releases.

Even though most reservoirs were built after the '50s, when downstream water rights were already in place, hydropower companies are free to release at their discretion. The result of this power asymmetry is exemplified by the dispute that arose during the extremely dry summers of 2003, 2005 and 2006. On those occasions, the Regional Authority imposed a forced release to the upstream hydropower companies in order to alleviate the drought conditions that were seriously threatening agricultural yields downstream (Riva, 2010). The resulting hydropower revenue losses led to a court litigation and a judgment that finally granted damages to the companies at the expense of the Regional Authority (Anghileri, 2014). Similar events show how the current management configuration is unable to cope with increased climate uncertainty and weather extremes. A recent study on the same area (Anghileri et al., 2012) proved a central planner type of management dominates the current uncooperative global performance and suggests induced cooperation may be an effective and inexpensive adaptation measure.

For this application, we consider a2a and Enel companies, which control more than 50% of the total upstream reservoir capacity, as the upstream agents maximizing hydropower production (red triangles in Fig. 2) and the Adda Consortium as the downstream agent whose local objective is ensuring adequate water supply. Flood protection is considered as a concurrent objective of the Adda Consortium but is then treated as a constraint, assuming an historically acceptable threshold. The regional water authority is the regulatory third party applying the HCM to the system.

3.2. The system model

The system model describes the operations of two upstream hydropower reservoirs (run by a2a and Enel companies respectively) and

Lake Como, regulated by the Consorzio dell'Adda. We adopted a conceptual model assuming a 24 h decision time-step while the hydropower price dynamic is modeled hourly. The model was used to optimize the system operation under both UC and FC management configuration as detailed in Section 2.2. The formulation of the objectives for each system component is given in the next paragraphs.

The lake dam operation

As discussed in the above section, the lake regulation aims at satisfying the two main objectives of flood control and water supply. Thus, on the basis of previous works (Anghileri et al., 2011; Culley et al., 2016), we formulate the following objectives computed over the evaluation horizon H:

Flood control: the annual average number of days [day/year], when a flood occurs, computed as

$$J^{flo} = \frac{1}{N_y}\sum_{t=0}^{H-1} g_{t+1}^{flo} \quad \text{where}$$
$$g_{t+1}^{flo} = \begin{cases} 1 & \text{if } h_{t+1} > \bar{h} \\ 0 & \text{otherwise} \end{cases} \tag{6}$$

where h_t is the lake level, N_y is the number of years in the horizon and $\bar{h}$ is the flood level threshold equal to 1.24 m which determines the occurrence of a flood in Como city.

- Water supply: the average squared daily water deficit [$(m^3/s)^2$], computed as

$$J^{irr} = \frac{1}{H}\sum_{t=0}^{H-1} g_{t+1}^{irr} \quad \text{where}$$
$$g_{t+1}^{irr} = (\max(w_t - (r_{t+1} - q^{ef}), 0))^2 \tag{7}$$

where w_t is the daily water demand, r_{t+1} is the release from the lake and q^{ef} is the environmental flow equal to 5 m^3/s.

The square of the irrigation step cost accounts for crop vulnerability by penalizing higher shortages, which are more likely to compromise the crop growth, with respect to more frequent but smaller shortages, which are less dangerous to the crops (Hashimoto et al., 1982).

Hydropower reservoirs operation

As a simplified version of the real system, where a2a and Enel combined operate four reservoirs and seven hydropower plants, the model considers one equivalent reservoir and plant for each company: the maximum flow Q_{eq} for an equivalent plant is set as the minimum between the maximum flows of each original plant and the equivalent energetic coefficient k_{eq} is the sum of the coefficient of the aggregated plants.

The model assumes that the daily energy produced by each plant at its maximum capacity is:

$$G_M = k_{eq} \cdot Q_{eq} \cdot 3600 \tag{8}$$

In order to maximize their profit, hydropower companies tend to release the maximum amount of water that can be generated by each plant Q_{max} during the most profitable hours of the day according to the national electricity price (PUN) determined by the Italian energy market.

Thus, given the release r_{t+1}, the number of functioning hours Δ is uniquely determined for each plant as:

$$\Delta = \frac{r_{t+1} \cdot 24}{Q_{max}} \tag{9}$$

The aim of the operation for both a2a and Enel is to maximize the yearly revenue. Therefore, for each company $c = 1, 2$ we formulate the objective:

$$J_c^{HP} = \frac{1}{N_y}\sum_{t=0}^{H-1} g_{t+1,c}^{HP} \quad \text{where}$$
$$g_{t+1,c}^{HP} = G_{M,c} \cdot \Delta \cdot Pe_{t+1,\Delta} \tag{10}$$

Where $Pe_{t+1,\Delta}$ is the sum of the first Δ hourly energy prices for day t +1.

3.3. Experimental setting

The experimental setting is characterized as follows:

- *Optimization under UC and FC management scenario*: we modeled both the uncooperative and the fully cooperative policies assuming self-interested agents maximizing their individual utility function (i.e., individual rationality) (Giuliani et al., 2016b). The UC solutions are the result of a two-step procedure which first involves optimizing the upstream hydropower releases by two (one for each hydropower company) single-objective problems, i.e., Problem (1) where $\mathbf{J} = J_c^{HP}$ for Enel and a2a respectively. The release trajectories produced by the resulting policies are then set as inflows to the lake to solve a bi-objective problem for Lake Como where $\mathbf{J} = [J^{flo}, J^{irr}]$. This procedure generates a set of UC solutions with varying flood/irrigation trade-offs. The flood objective is later treated as a constraint to identify one single UC solution. The FC solutions are obtained by solving Problem (1) including all objectives at once, in this case $\mathbf{J} = [J_1^{HP}, J_2^{HP}, J^{flo}, J^{irr}]$. This optimization produces a multi-dimensional Pareto front that is later sliced into a single plane by treating the flood objective as a constraint and considering $J^{HP} = \sum_{c=1,2} J_c^{HP}$.
  All problems are solved with the Evolutionary Multi Objective Direct Policy Search (EMODPS) method (Giuliani et al., 2016a), an approximate dynamic programming approach that combines direct policy search, nonlinear approximating networks, and multi-objective evolutionary algorithms. In particular, we parameterized the operating policy as Gaussian radial basis functions, as they have been demonstrated to be effective in solving this type of multi-objective policy design problems (Giuliani et al., 2014a; 2014b). To perform the optimization, we use the self-adaptive Borg Multi Objective Evolutionary Algorithm (MOEA) (Hadka and Reed, 2013), which has been shown to be highly robust in solving multi-objective optimal control problems, where it met or exceeded the performance of other state-of-the-art MOEAs (Zatarain-Salazar et al., 2016). Each optimization was run for 1 million function evaluations over the evaluation horizon 2006–2014. The PUN data we used refer to the period 2009–2015 because, collected after the introduction of solar power subsidies and the economic crisis, they are both internally homogeneous and able to reproduce the most recent winter price peak which is further challenging the upstream/downstream relationship. To improve solution diversity and filter out the randomness of both the initial population set and the optimization operators, the solution set for each optimization is the result of 20 random optimization trials. The final optimal policies for each experiment are defined as the set of non-dominated solutions.
- *Constraint design and application*: three dynamic minimum release constraints are designed for each of the two hydropower companies (six in total). A dynamic constraint is described by the pair minimum permitted release from a hydropower reservoir and associated lake storage. The latter are discretized values. The former are sampled from the release trajectories of three selected fully cooperative solutions FC_1, FC_3 and FC_5 for the two hydropower companies during the most critical months for irrigation (August–September) (Anghileri et al., 2012). Typically, a higher minimum release is associated with a lower lake storage.
  The six constraints are then applied to the UC policies of each company during the agricultural season (May–September) and

evaluated over the simulation horizon 2006–2014.

- *Index-based contracts design*

  a. Setting the index

  Since no historic revenue data is available, we search for an index with high correlation to the historic energy production (which can be drawn from the historic releases). Index correlation with the simulated historical revenues is also evaluated. Based on state of the art literature, we evaluated the inflow to each of the two reservoirs (a2a and Enel's) aggregated over different lag times (weekly, monthly, seasonal and yearly). The index with the highest correlation (R^2 = 0.89 and 0.84 for a2a and Enel respectively) was the inflow volume over the hydrological year (starting the 1st of April, at the beginning of the snow melt season and reservoir recharge period). Alternative combined indexes, including snow measurement, the price of electricity and/or the Italian electricity demand, were also evaluated, but none of them produced a significant variation in R^2. Correlation of the inflow volume over the current hydrological year with the simulated historical revenues confirmed the observed inflow-power production correlations: R^2 was 0.85 and 0.84 for a2a and Enel respectively.

  b. Defining the payout function

  We designed 8 insurance contracts ($I_{1\dots8}$) each providing a different level of risk coverage. The payout function parameters (strikes and slopes) are calibrated over the simulation horizon. The strikes were set as percentiles of the index for the two companies. In particular, the strike S ranged from the 30th to the 70th percentile of the inflow in the insurance portfolio. As in Foster et al. (2015), a fixed slope was computed as the ratio of average revenue in the contract period on average inflows.

  c. Pricing the contract

  The Wang transform method was used for pricing the contracts as described in Section 2.3. As a commonly accepted value when pricing weather contracts (Foster et al., 2015; Kern et al., 2015; Wang, 2000) we assumed a market price of risk value (λ) of 0.25 (see Eq. (4)).

  d. Timing

  We assume the hydrological year starts on the 1st of April, at the beginning of the snow-melt season. While the yearly autocorrelation on the inflows was not relevant ($R^2 < 0.1$), snow pack data, available before the 1st of April, are correlated to the next twelve months total inflow and therefore provides knowledge on the future payouts. To avoid adverse selection and ensure that both the insurer and the insured have similar knowledge on future risks, the execution date was set to precede the effective date of 5 months (i.e., the 1st of October) when most of snow deposition has yet to take place.

- *Index-based contracts evaluation*: the contracts adoption is simulated over the horizon 2006–2014 as well as over a 200 year synthetic inflow time series, under three possible HCM agreements:
  a. A fully subsidized agreement, where the Water Authority pays the entire premium for index-based insurance covering both hydropower companies (solution HCa).
  b. A partly subsidized agreement, where the Water Authority and the hydropower companies equally share the cost of the insurance premiums (solution HCb).
  c. A non-subsidized agreement, where the hydropower companies contribute to the entire premium (solution HCc).

  The subsidized configurations, HCa and HCb, are compared to a non insured scenario (direct compensation). The contracts are also evaluated through a series of financial metrics further detailed in Appendix A.
- *Synthetic time series*: the uncooperative and fully cooperative policies, as well as the insurance mechanisms were also evaluated over a 200 year synthetic inflow time series. To generate synthetic inflows to a2a and Enel reservoirs and the residual inflow to Lake Como (i.e., the inflow to the lake not influenced by the considered upstream hydropower reservoirs), we used the k-Nearest Neighbor (KNN) algorithm (Nowak et al., 2010). KNN method is capable of generating a synthetic dataset that maintains the principal statistical characteristics of the historical data it is based on: we first generated yearly spatially aggregated data through an annual AR(1) model and then disaggregated it in space and time based on the intra annual daily volumetric percentages observed in the historical record from the period 1996–2014. A different synthetic dataset generated from the same historic period was used for calibrating and validating the contracts.

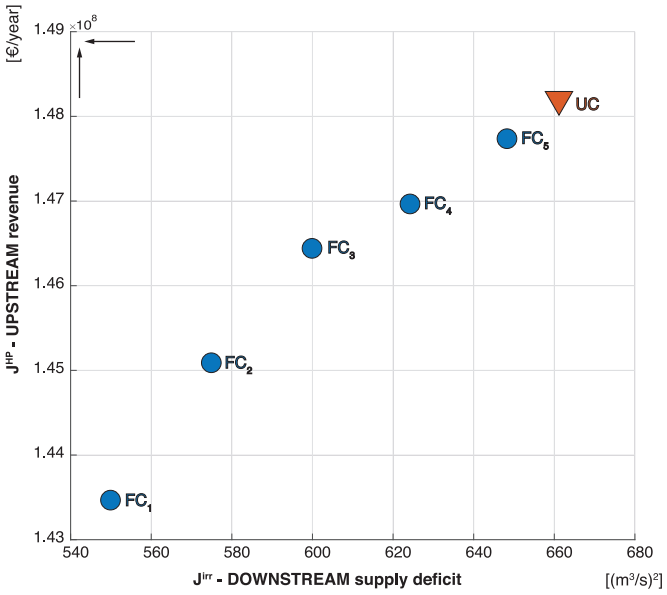

Fig. 3. Selected optimal UC and FC solutions. The arrows indicate the direction of preference. The $FC_{1\dots5}$ and UC solutions are shown on the same plane J^{flo} = 5.8 days/year.

4. Results

4.1. UC and FC policies identification

The uncooperative and fully cooperative policies are modeled as detailed in Section 3.3. Results are displayed in Figs. 3 and 4. Given the geographic system configuration, the two equivalent hydropower reservoirs are always operated without interfering with each other. This implies that, even in the fully cooperative case, their objectives are never conflicting. Therefore, in our analysis, the hydropower objective J^{HP} aggregates the yearly revenues of the two hydropower companies. Moreover, as mentioned in Section 3.3, the flood objective is considered both in the UC and the FC optimization, but is later treated as a constraint in order to better investigate the water-supply/hydropower trade-off. To this end, we assumed the historically accepted threshold of about 6 days of flood in a year. Fig. 3 compares the fully cooperative and uncooperative solutions on the same J^{HP} vs. J^{irr} space which lies on the plane J^{flo} = 5.8 days/year. As expected, the FC Pareto front, which is the performance of the Pareto optimal set, covers different alternative upstream/downstream trade-offs, while the UC solution represents one of the extremes, which maximizes the hydropower objective at the expense of the downstream water supply goal. This result exemplifies the system power asymmetry. These solutions are obtained from two separate optimization efforts, one for the UC and one for the FC case, which are presented in Fig. 4.

Panel 4a shows the performance of the Pareto efficient FC alternatives FC_i. The FC optimization solves a problem with four objectives $\mathbf{J} = [J_1^{HP}, J_2^{HP}, J^{flo}, J^{irr}]$, here we aggregated the non conflicting hydropower revenues of the two companies $J^{HP} = \sum_{c=1,2} J_c^{HP}$ to show a three

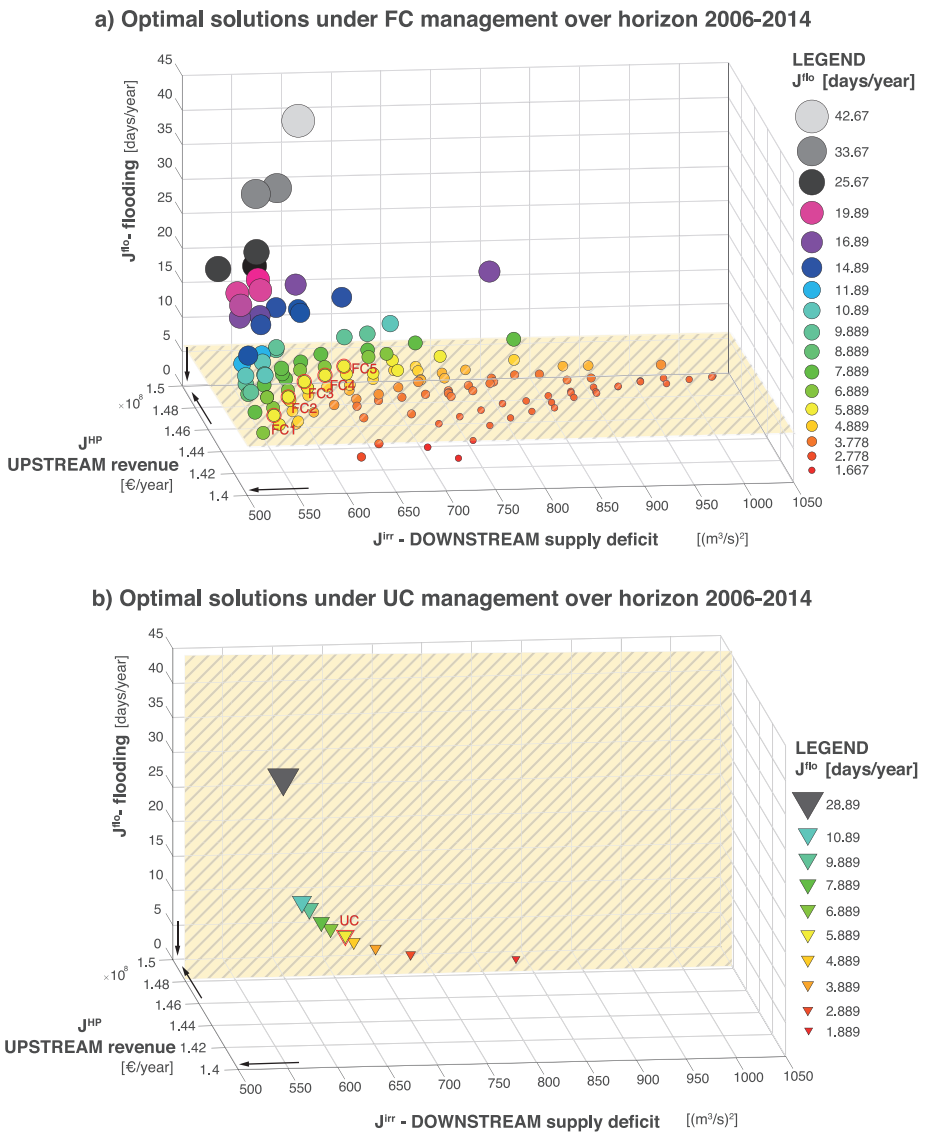

Fig. 4. Results of the first step in the methodology i.e., the system optimization under FC and UC management configurations. The arrows always indicate the direction of preference. Bigger symbols correspond to higher values of J^{flo}. Panel a) shows the FC Pareto front, which is the performance of the Pareto optimal set, over the optimization horizon. The red circled solutions $FC_{1...5}$ are the ones equally performing w.r.t the flood objective, on the plane $J^{flo} = 5.8$ days/year. Panel b) depicts the UC Pareto front on the plane $J^{HP} = 1.483 \times 10^8$ € /year. The selected UC solution whose J^{flo} performance is 5.8 days/year is highlighted in red. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

dimensional Pareto front. The arrows indicate the direction of preference: ideally we search for a solution minimizing the irrigation deficit (horizontal axis) and the yearly number of floodings (vertical axis, also indicated by degrading colors and bigger dimension for higher values) while maximizing the hydropower revenue (lateral axis). Not surprisingly, we observe that the water-supply/hydropower trade-off is less and less evident when the conditions on the flood objective are relaxed. In other words, reducing the conflict between the two objectives of the downstream agent enlarges the space for compromise solutions upstream and downstream. This result indicates that, if the lake regulation's only target was water allocation, the downstream water demand would be satisfied almost independently from the hydropower releases. Therefore, we selected the set of centralized solutions $FC_{1...5}$ equally performing with respect to the flood objective on the plane $J^{flo} = 5.8$ days/year (depicted in yellow in Fig. 4) which represents an historically acceptable value.

Panel 4b shows the performance of the Pareto efficient uncooperative alternatives. As mentioned, the value of the hydropower objective J^{HP} aggregates the result of two independent single objective optimizations. For this reason, all UC solutions' performance rests on the same plane (depicted in yellow in Fig. 4) defined as $J^{HP} = 1.483 \times 10^8$ € /year. Similarly to $FC_{1...5}$, the selected UC solution is the one satisfying the assumed condition on the flood objective of 5.8 days per year.

4.2. Dynamic minimum release constraints

Three dynamic minimum release constraints are derived from three fully cooperative solutions exploring different trade-offs between hydropower production and water supply. As described in Section 2.2, for each hydropower company we considered the release trajectories of alternatives FC_1, FC_3 and FC_5. Fig. 5 shows the three constraints derived for company a2a in ascending order of severity. Each constraint is represented by the coupled values of minimum release and lake storage, as sampled from the corresponding FC_i trajectory. As can be noted from the plots, in a FC solution a lower storage always implies a larger minimum release. On the other hand, a FC solution with a higher preference for irrigation benefits (i.e., FC_1 over FC_3 over FC_5) produces a constraint that is active for higher lake storage values and requires larger release volumes.

Fig. 6a depicts the simulated performance for both companies of the UC policy under the three constraints averaged over the evaluation horizon 2006–2014 (i.e., CC_1, CC_3 and CC_5). The average yearly effect of the constraints is a general decrease in hydropower revenues. The most severe constraint CC_1 leads to a revenue loss of 1.8×10^6 €/year, equivalent to 1.2% of the yearly average revenue. On the other hand, the water supply deficit is reduced by 3.3%. The effects of CC_3 and CC_5 are less evident, leading to a J^{irr} improvement of 0.9% and 0.1%

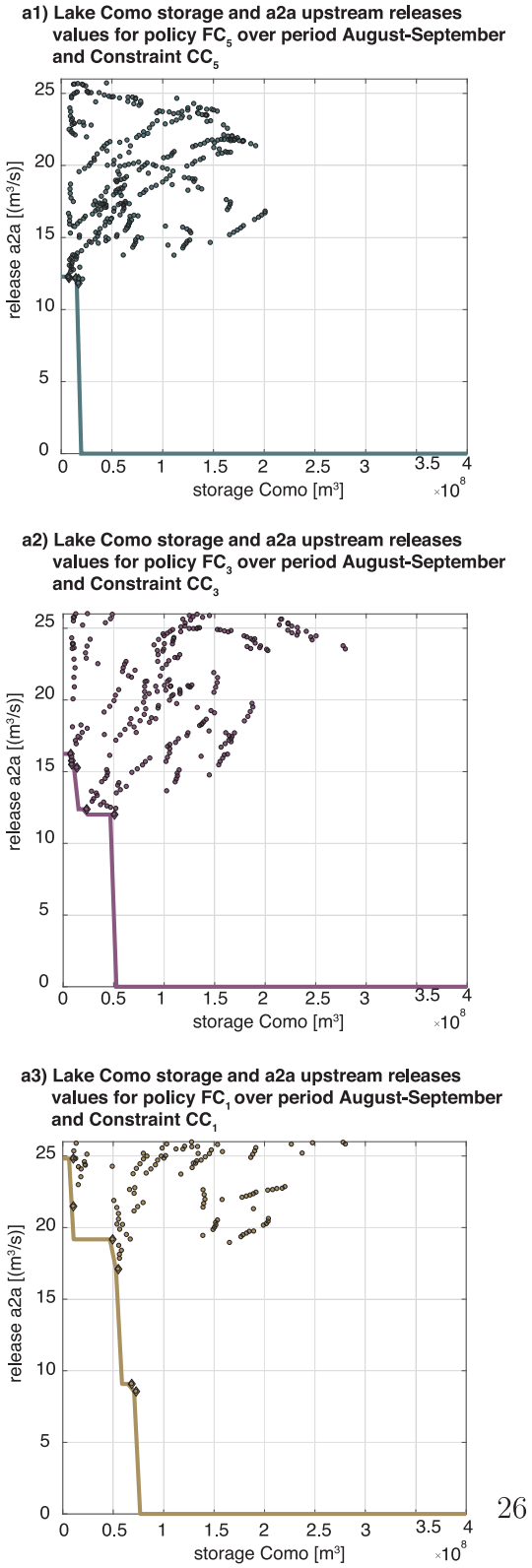
a1) Lake Como storage and a2a upstream releases values for policy FC5 over period August-September and Constraint CC5
release a2a [(m3/s)]
storage Como [m3]
×10^8
a2) Lake Como storage and a2a upstream releases values for policy FC3 over period August-September and Constraint CC3
release a2a [(m3/s)]
storage Como [m3]
×10^8
a3) Lake Como storage and a2a upstream releases values for policy FC1 over period August-September and Constraint CC1
release a2a [(m3/s)]
storage Como [m3]
×10^8

Fig. 5. Constraint design for company a2a from centralized solutions FC_5, FC_3 and FC_1 respectively. The circles correspond to observed coupled values of upstream release and downstream storage. The lines connect the minimum admissible releases for each discretized lake storage value.

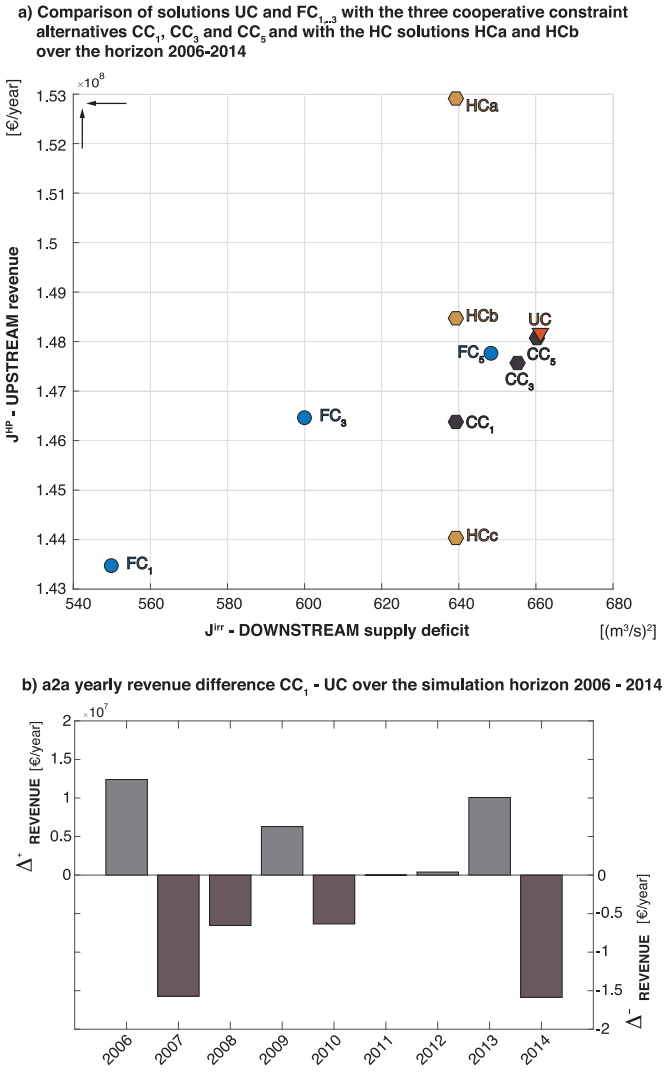
a) Comparison of solutions UC and FC1,..3 with the three cooperative constraint alternatives CC1, CC3 and CC5 and with the HC solutions HCa and HCb over the horizon 2006-2014
J^HP - UPSTREAM revenue [€/year]
J^irr - DOWNSTREAM supply deficit [(m3/s)2]
HCa
HCb
UC
FC5
CC5
CC3
FC3
CC1
HCc
FC1
b) a2a yearly revenue difference CC1 - UC over the simulation horizon 2006 - 2014
Δ+ REVENUE [€/year]
Δ- REVENUE [€/year]

Fig. 6. Panel a) compares the UC and the FC solutions with the three cooperative constrained alternatives CC_1, CC_3 and CC_5 (in black) and the HC solution under the three considered agreement configurations HCa, HCb and HCc (in yellow). J^{HP} on the y axis is the yearly average over the simulation horizon of the aggregated revenues for the two companies, therefore the performance of each CC_i/HC solution is determined by the combined effect of both a2a and Enel's constraints/contracts. The arrows show the direction of preference. Panel b) shows the difference in yearly revenue caused by constraint CC_1 on company a2a for each year over the simulation horizon 2006–2014. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

respectively and smaller revenue losses (0.4% and 0.1%). It is worth mentioning that despite these constraints negatively impact on the self-interested hydropower operations producing significant revenue losses to the two companies, the effect of these direct measures in terms of energy production is fairly negligible.

The yearly average revenue variation may not appear very large. However, if we consider the effect of the constraint on each year revenue (Panel 6b), we can observe a significant change. Hydropower production is naturally prone to supply risk, a form of financial risk linked to the availability of the supply source (i.e., water) and aggravated by hydrologic uncertainty. The application of forced releases that are triggered by dry conditions downstream is likely to exacerbate such a financial risk for hydropower companies in dry years. As a result, we expect the constraints to cause a revenue loss whenever the inflow volume and its timing do not allow for both satisfying the imposed rule and optimizing power generation. However, the minimum release constraint can lead to higher hydropower revenues in wet years. This positive difference is due to the stochastic optimization we used for designing the hydropower policy, which, in the presence of inflow uncertainty, prefers to act conservatively and release less water to avoid the risk of emptying the reservoir. However, in wet conditions it would

have been possible to release more - and hence produce more - as future, higher than expected inflows are able to refill the reservoir. The constraint is by chance forcing some releases in these days, ultimately producing higher revenues. The yearly mean value levels out the effect of the constraint since it averages both positive and negative variations. Panel 6 b exemplifies this concept by showing the effect of the forced release CC_1 on a2a revenues over the horizon 2006–2014. Both 2006 and 2007 were fairly dry years, nevertheless, in 2006 the storage is enough to comply with the minimum release rule while still allocating water to the most profitable hours during the rest of the year. However, the effect of the constraint over the next two years results in a cumulative loss of about 21 million € . The next years illustrate a similar pattern, with alternating wet/dry conditions determining different and sometimes significant positive or negative financial outcomes. The effect of the constraints on the two companies is similar, though it is a lot less visible for Enel which manages smaller water volumes.

4.3. Index-based contracts

To contrast the variability in revenue losses induced by the constraint, we apply the 8 different index-based insurance $I_{1...8}$ (designed as described in Section 3.3) to the CC_i solutions. The effect of financial risk instruments is typically more evident when observing the revenue trajectories over a long time series, as short time series have a high variance and, therefore, they show larger deviations from the mean (i.e., the expected damage used to define the premium). Fig. 7 shows both the revenue trajectories of the uninsured alternative CC_1 (blue line) and the insured alternative HCb (red line) for company a2a and contract I_2. This contract was chosen for this particular company and constraint combination because it provides the highest Risk Mitigation Level for the lowest marginal cost (for a detailed comparison, see Appendix A). As a direct consequence of adopting a risk mitigation measure, revenues are less vulnerable to the hydrologic uncertainty: the red trajectory is visibly more constant, the negative peaks are smothered by the large payouts received on dry years (green areas in Fig. 7), while the yearly premium reduces the positive peaks (red areas). However, the risk of a low or very low revenue due to scarce inflow (i.e., supply risk) is borne by the insurance company, thus largely improving the worst case performance, or revenue floor (the red dashed lines in Fig. 7). These observations hold true for all designed contracts and independently from who will contribute to the insurance premium.

The last step of our methodology (see Fig. 1) requires the adoption of a financial measure able to guarantee the constraint acceptability and the transition to a new equilibrium outcome. Therefore we simulated the adoption of different index-based contracts under a fully subsidized (HCa) a partially subsidized (HCb) and a non-subsidized agreement (HCc). This approach is highly adjustable (e.g., different levels of subsidies and contract combinations can be adopted) therefore allowing for a flexible and negotiable measure. Fig. 6a shows the performance of the three alternative HC agreements HCa, HCb and HCc under contract I_2 and constraint CC_1 over horizon 2006–2014 (in yellow). In all cases, the companies receive a payout from the insurance whenever the index insurance is triggered by low inflow conditions (i.e., yearly inflow volume lower than the S threshold). It is relevant to note that the index which triggers the payout is decoupled from the conditions activating the constraint (i.e., downstream storage values). For each agreement scenario, the resulting shift in yearly revenue performance is a combination of the received payouts and the respective premium share that is paid to the insurance company. Since yearly premiums are designed to exceed the expected payout value (i.e., the loading principle), solution HCc produces a negative shift in yearly revenue performance, while a positive shift is observed when the regional water authority contributes to the premium (solutions HCa and HCb). One should consider however, that yearly revenue represents only one of the primary goals of hydropower companies, which may include financial stability as well. Considered in this light, solution HCc could still be a valid alternative to a non-insured scenario (CC_1), especially for mitigating the impacts of extreme events. The J^{HP} performance associated to HCa and HCb exceed the UC solution by 4.7 and 0.29 million € respectively. In these cases, the Water Authority has internalized the costs by contributing to the total insurance premium (8.9 million € under HCa or half of it under HCb). These are just three possible agreement examples, we can anticipate the final arrangement to emerge from a bargaining process possibly involving additional incentives (e.g., license granting) and being fine-tuned to account for contingencies.

4.4. Comparison to a direct form of compensation

Subsidized index-based contracts proved to be effective in restoring the hydropower revenues to the UC conditions. The cost for the Water Authority could be contributing to paying the insurance premiums in full (HCa) or in part. An alternative form of compensation, directly covering the revenue losses induced by the minimum release constraints, has the main drawback of depending on uncertain hydrology and of being highly variable from year to year (i.e., high financial risk). Fig. 8 compares the costs for the Water Authority of solutions HCa, HCb (i.e., the entire premium or half of it, indicated by the red dashed lines) with the direct compensation of constraint CC_1 for company a2a (the brown negative bars). In this case, it is evident how the insurance

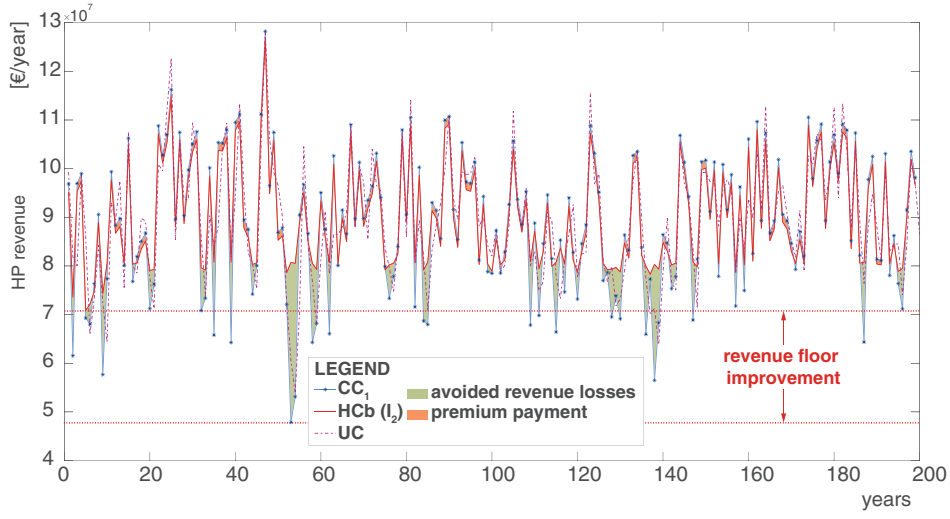

Fig. 7. Revenue trajectories relative to the uninsured alternative CC_1 (blue line) and the insured alternative HCb (red line), over 200 year synthetic inflow time series. Green areas indicate the insured revenue is higher than in the uninsured case. The opposite is true for red areas. The red dashed lines indicate the worst case performance for the uninsured and insured alternatives and show the revenue floor improvement in the latter case. The dashed magenta lines represent the trajectory of the UC scenario. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

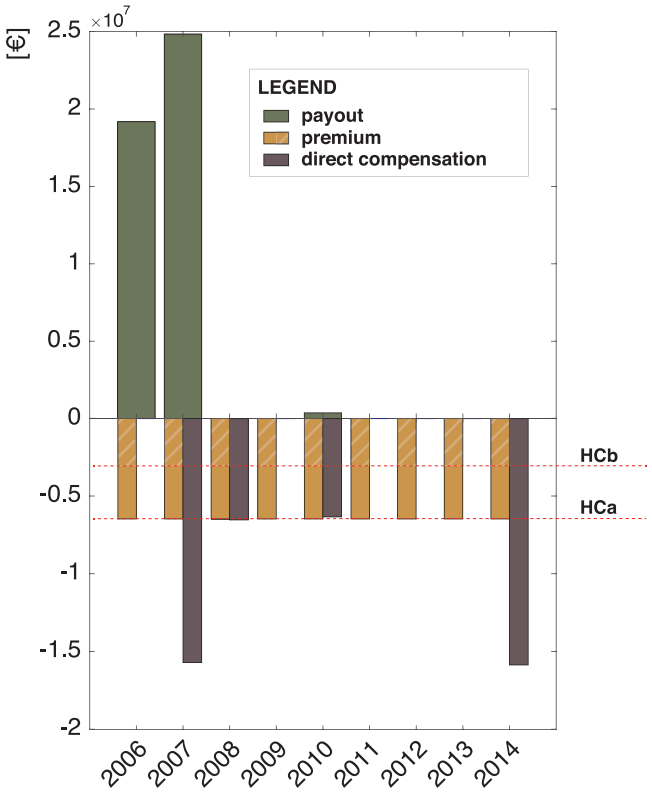

Fig. 8. Yearly payouts (in green) and premiums (in yellow) for contract I_2 and company a2a are compared with the revenue losses induced by constraint CC_1 on a2a (brown) which is also the cost of a direct compensation for the Water Authority. This cost can be compared with the alternative costs for the Water Authority of imposing the HCM under agreements HCa and HCb (red lines). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

solution I_2 offers compensation at more constant, deferred prices (maximum yearly cost is about 6.8 million € for HCa and 3.4 million € for HCb compared to a maximum direct compensation cost of 15.9 million €), which is usually preferable and more practicable, but, generally, at a higher average cost (the yearly average cost is equal to the maximum average cost for both HCa and HCb compared to an yearly average direct compensation cost of 4.9 million €). In this case, the agreement *HCb* also provides for a cheaper alternative for the Water Authority.

This conclusion, however, is not equally straightforward or generalizable to other combinations of constraint, company and contract. The main reason for this is that while direct compensation varies according to the constraint, the insurance premium is essentially independent of it. In the case of Enel, which is less affected by the constraints than a2a, a direct compensation may be the cheaper solution for the Water Authority. On the other hand, the hydropower companies are likely to prefer an indirect financial solution given the additional benefits offered by index-based contracts (reduced revenue fluctuations, increased revenue floor). This fact, together with the high flexibility of insurance contracts, could lead to fine-tuned agreements between the Water Authority and the hydropower companies (e.g., a different premium share combination).

5. Conclusion

In power asymmetric water systems, where the absence of reciprocal interdependency hinders a balanced water rights distribution, cooperative actions may be induced via positive linkages (e.g., side-payments) (Dinar, 2006; Mitchell and Keilbach, 2001). However, practical and financial issues arise when the magnitude and timing of these payments depend on hardly predictable conditions (e.g., future hydrology). In this paper, we propose the use of index-based insurance contracts to mitigate the financial risk associated with uncertain side payments and concurrently provide a flexible tool for sharing externalities in a power asymmetric river basin. More in detail, we designed a Hybrid Cooperation Mechanism to foster collective action in a water system with multiple agents characterized by geographic power asymmetry. The approach is demonstrated in the Lake Como system, where the upstream hydropower companies are granted licenses to freely release their stored water in time irrespective of the timing of downstream users' demands. In this context, the intervention of a regulatory third party (i.e. the Regional Water Authority) can enforce more balanced solutions.

The direct part of the HCM is a dynamic minimum release constraint imposed over upstream releases that is based on the downstream agent policy (i.e., the lake storage). This measure is able to improve downstream performance up to 3.3% by introducing a mutual upstream/downstream relationship. Conversely the yearly hydropower revenue is reduced up to 1.2% on average. However, because it largely depends on hydrology, this loss pattern displays relevant inter-annual fluctuations, with dry years resulting in significant revenue losses. The constraint acceptability is, therefore, addressed by an instrument able to manage this variability: an index-based insurance contract which constitutes the indirect component of the HCM.

We have considered the cost of a similar measure for the Regional Authority under totally and partially subsidized premium agreements and observed that, depending on the given case, weather derivatives may provide a cheaper alternative with respect to a direct compensation. However, we should consider that the insurance would also provide further benefits to the hydropower companies. Financial stability in the form of supply risk mitigation and revenue floor improvement. For this reason, it is likely this solution would be preferred by the hydropower producers who may be willing to bear a substantial part of the premium. This latter case is also preferable because it would further incentivize the companies to modify their release policies in order to adapt to the constraint and reduce its impact on their revenues. Finally, contributing in paying the insurance premium might be an important aspect to be included in the incoming renegotiation of the water rights of the hydropower companies.

We consider the proposed hybrid approach to be readily transferable to larger and more complex systems similarly affected by geographic power asymmetry e.g., the Zambezi (Gandolfi and Togni, 1997; Giuliani and Castelletti, 2013; Tilmant et al., 2010; 2012), and the Euphrates–Tigris (Altinbilek, 2004; Kibaroglu and Ünver, 2000). Moreover, the use of insurance contracts as bargaining tools is applicable to many other different other contexts, especially when a newly imposed condition is expected to generate a financial risk which is borne by only one party to the negotiating process.

Future research efforts will focus on exploring alternative mechanism, especially the possibility of introducing financial coverage for the downstream farmers. Yet, this implies the adoption of a distributed model (in space and time) for the downstream users, able to take into account the different crops with their phenology, the resultant agricultural production, and farmers' revenues (Li et al., 2017). This model would also allow comparing the premium paid by the hydropower companies or the regional authority with respect to the gain in terms of agricultural profit.

To conclude, financial hedging tools offer a reliable and practicable alternative to favor a more balanced and politically acceptable management of multi-purpose water systems characterized by power asymmetry. Such finding is relevant especially in times where granting of licenses is often being reviewed to include environmental protection and equity issues.

Acknowledgment

This work was partially supported by the SOWATCH project funded by Fondazione Cariplo (grant number 2015-0220).

Appendix A. Weather derivatives evaluation

To evaluate a contract, many aspects have to be considered. A risk-mitigation tool provides a strategy for reducing inter-annual variability and hedge large damages, but the desired level of coverage depends on many factors, including the buyer loss and risk aversion. For this reason, we considered a series of diverse measures to assess the index-based portfolio designed for Lake Como case study. The values for the designed insurance contracts $I_{1..8}$ are shown in Table A.1.

The first values to weigh, are the contract premium P, the expected payout E[p] and their difference, or loading L. The loading percentage on the expected value of payouts is particularly informative on the existing trade-off between premium and loading concurrent minimization. In fact, the contract loading increases as the variance of a payout distribution grows: if the strike value S is intended to cover the insured from the low-frequency big-events, the contract loading will be high on a small premium. On the other hand, high-frequency small events would be covered by insurances with a lower loading and a higher premium.

To compare the contracts with different strike levels, the contract cost (i.e. the portion of the premium that is not actually returned to the buyer in the form of payouts over the contract period) is evaluated and expressed as a percentage on the yearly average revenue $\overline{R}$:

$$cost = \frac{P - p}{\overline{R}} \tag{A.1}$$

Higher strikes provide a better coverage for a higher cost.

The already mentioned revenue floor, is expressed in terms of Risk Mitigation Level (RML), the ratio of minimum revenues R with and without

Table A1
Assessment of different weather derivatives solutions for each company and constraint scenario. Eight index-based insurance contracts $I_{1..8}$, with strike values ranging from the 30th to the 65th index percentile, are evaluated over the considered horizon 2006–2014. Other than the premium (P) and the expected payout (E[p]), a series of metrics are taken into account such as the Loading (L), the cost, the Risk Mitigation Level (RML) and the revenue fluctuation (*fluct*).

			P [$\frac{\times 10^6 €}{year}$]	E[p] [$\frac{\times 10^6 €}{year}$]	p_{max} [$\frac{\times 10^6 €}{year}$]	L [%]	cost [%]	RML [/]	*fluct* [$\frac{\times 10^6 €}{year}$]
a2a	CC_1	I1	6.693	4.846	24.58	38.11	1.773	1.236	8.669
a2a	CC_1	I2	6.803	4.932	24.83	37.94	1.796	1.238	8.612
a2a	CC_1	I3	7.106	5.176	25.43	37.29	1.852	1.242	8.460
a2a	CC_1	I4	8.081	5.973	27.23	35.30	2.024	1.252	8.018
a2a	CC_1	I5	9.056	6.770	29.02	33.78	2.195	1.263	7.668
a2a	CC_1	I6	9.072	6.783	29.04	33.75	2.197	1.263	7.662
a2a	CC_1	I7	9.088	6.796	29.07	33.71	2.199	1.263	7.656
a2a	CC_1	I8	9.970	7.578	30.24	31.56	2.296	1.267	7.303
a2a	CC_3	I1	6.762	4.896	24.83	38.11	1.773	1.223	7.965
a2a	CC_3	I2	6.873	4.983	25.09	37.94	1.796	1.222	7.930
a2a	CC_3	I3	7.179	5.229	25.69	37.29	1.852	1.223	7.820
a2a	CC_3	I4	8.164	6.034	27.51	35.30	2.024	1.215	7.507
a2a	CC_3	I5	9.150	6.839	29.32	33.78	2.195	1.203	7.305
a2a	CC_3	I6	9.165	6.853	29.34	33.75	2.197	1.203	7.300
a2a	CC_3	I7	9.181	6.866	29.37	33.71	2.199	1.203	7.296
a2a	CC_3	I8	1.007	7.656	30.55	31.56	2.296	1.206	6.995
a2a	CC_5	I1	6.795	4.920	24.95	38.11	1.773	1.199	7.789
a2a	CC_5	I2	6.906	5.007	25.21	37.94	1.796	1.198	7.756
a2a	CC_5	I3	7.213	5.254	25.82	37.29	1.852	1.198	7.646
a2a	CC_5	I4	8.203	6.063	27.64	35.30	2.024	1.186	7.324
a2a	CC_5	I5	9.194	6.872	29.46	33.78	2.195	1.174	7.119
a2a	CC_5	I6	9.209	6.886	29.48	33.75	2.197	1.174	7.113
a2a	CC_5	I7	9.225	6.899	29.51	33.71	2.199	1.174	7.108
a2a	CC_5	I8	1.012	7.693	30.70	31.56	2.296	1.178	6.833
Enel	CC_1	I1	1.364	0.991	5.026	37.71	0.909	1.043	2.932
Enel	CC_1	I2	1.602	1.174	5.623	36.45	1.041	1.053	2.916
Enel	CC_1	I3	1.775	1.311	5.988	35.36	1.128	1.048	2.894
Enel	CC_1	I4	2.091	1.570	6.574	33.20	1.268	1.048	2.836
Enel	CC_1	I5	2.838	2.194	7.822	29.37	1.568	1.052	2.733
Enel	CC_1	I6	3.585	2.818	9.070	27.24	1.868	1.032	2.791
Enel	CC_1	I7	3.911	3.095	9.576	26.36	1.986	1.028	2.825
Enel	CC_1	I8	4.096	3.257	9.836	25.77	2.042	1.030	2.824
Enel	CC_3	I1	1.368	0.993	5.040	37.71	0.909	1.043	2.827
Enel	CC_3	I2	1.606	1.177	5.637	36.45	1.041	1.053	2.816
Enel	CC_3	I3	1.779	1.314	6.004	35.36	1.128	1.048	2.802
Enel	CC_3	I4	2.096	1.574	6.591	33.20	1.268	1.048	2.757
Enel	CC_3	I5	2.845	2.199	7.843	29.37	1.568	1.052	2.681
Enel	CC_3	I6	3.595	2.825	9.094	27.24	1.868	1.031	2.768
Enel	CC_3	I7	3.921	3.103	9.601	26.36	1.986	1.027	2.813
Enel	CC_3	I8	4.107	3.266	9.861	25.77	2.042	1.029	2.817
Enel	CC_5	I1	1.368	0.993	5.040	37.71	0.909	1.043	2.743
Enel	CC_5	I2	1.606	1.177	5.638	36.45	1.041	1.053	2.727
Enel	CC_5	I3	1.780	1.315	6.005	35.36	1.128	1.048	2.714
Enel	CC_5	I4	2.097	1.574	6.593	33.20	1.268	1.048	2.668
Enel	CC_5	I5	2.846	2.200	7.844	29.37	1.568	1.052	2.591
Enel	CC_5	I6	3.595	2.826	9.095	27.24	1.868	1.031	2.684
Enel	CC_5	I7	3.922	3.104	9.603	26.36	1.986	1.027	2.731
Enel	CC_5	I8	4.108	3.266	9.863	25.77	2.042	1.029	2.735

insurance:

$$RML = \frac{\min(R_{insured})}{\min(R_{uninsured})} \tag{A.2}$$

It is also interesting to evaluate the revenue fluctuation, computed as the standard deviation of the revenue throughout the whole period. This metric is able to reflect the uncertainty related to the yearly hydropower income. As already noted in Fig. 7, risk mitigation measures provide reduced revenue uncertainty and more constant income at the expense of a yearly premium. The higher the value S, the more pronounced the effect on variability.

In order to choose a contract for our application on company a2a and alternative CC_1, we considered the Regional Water Authority point of view, which is to find the cheapest alternative for mitigating the losses induced by the dynamic minimum release constraint. Taking into account the average yearly induced losses (about 4.9 million €), a low coverage is appropriate to provide full compensation. In this specific case we opted for the contract I_2 which offers the highest marginal RML for the lowest cost.

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